IEEE Guide for Determination of Hottest-Spot Temperature in Dry-Type Transformers

Sponsor

Transformers Committee of the IEEE Power Engineering Society

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IEEE-SA Standards Board

Abstract: Methodologies for determination of the steady-state winding hottest-spot temperature in dry-type distribution and power transformers with ventilated, sealed, solid cast, and encapsulated windings built in accordance with IEEE Std C57.12.01-1998 and IEC 60726 (1982-01) are described in this guide. Converter transformers are not included in this guide.
Keywords: ambient temperature, average winding temperature rise, dry-type transformer, production transformer, prototype transformer, temperature measurement, temperature sensors, transformer model, winding hottest-spot temperature

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Introduction

(This introduction is not part of IEEE Std C57.134-2000, IEEE Guide for Determination of Hottest-Spot Temperature in Dry-Type Transformers.)

The *hottest-spot allowance* is a number used in industry standards to establish the average temperature rise for rating purposes. The rated ambient temperature and hottest-spot allowance are subtracted from the rated insulation temperature class to determine the average temperature rise to be confirmed by thermal testing. IEEE Std 1-1986 states that the value of the hottest spot allowance is arbitrary, difficult to determine, and depends on many factors, such as size and design of the equipment. Based on the 1944 experimental works of Stewart and Whitman and Satterlee, standards used a hottest-spot allowance of 30 ºC for 80 ºC average temperature rise. The 30 ºC hottest-spot temperature allowance established in 1944 for 80 ºC average temperature rise was approximately correct for ventilated dry-type transformers produced at that time.

The 220 ºC insulation temperature class, 150 ºC average temperature rise, was initially used in sealed units. For these units, the 30 ºC hottest-spot temperature allowance was probably correct due to operation in the hotter inside gas. The 1959 Loading Guide, ANSI Appendix C57.96, used rated load limiting hottest spot temperatures of 150 ºC for ventilated units and 220 ºC for sealed units. In 1965, NEMA Standard TR 27 extended the 220 ºC insulation temperature class to ventilated units. In 1979, IEEE standard C57.12.01 also adopted the 220 ºC insulation temperature class for ventilated units. In both these documents, the 30 ºC hottest-spot allowance for the 220 ºC insulation temperature class was retained. In 1989, IEEE Std C57.12.01 and the Loading Guide IEEE C57.96 used a constant to 30 ºC hottest-spot allowance for all insulation temperature classes and all size transformers. IEC 60726 (1982-01) uses a variable hottest-spot allowance from 5 ºC to 30 ºC.

The winding hottest-spot temperature rise and average winding temperature rise are related by a ratio that is dependent upon such factors as the following:

a) Turn insulation
b) Winding height
c) Radial build
d) Ventilating ducts

From this relation, it is evidenced that no single winding hottest-spot temperature allowance is applicable to all types and ratings of transformers due to the variability of factors affecting the winding hottest-spot temperature. Laboratory test results reported by Pierce in 1993 validate this finding.

As a step to establishing appropriate temperature limits, the Dry-Type Hot-Spot Methodology Working Group was encouraged to report their findings on winding hottest-spot temperature measurements. Those reporting have confirmed the variability of the winding hottest-spot temperature ratio; however, the quantity of data compiled is insufficient for validation of winding hottest-spot temperature limits. To ensure consistency and repeatability of results, the working group decided to establish a methodology for determination of winding hottest-spot temperature by testing for qualification of a design family or mathematical model, and by testing or calculation for validation of production units.

This guide represents the state-of-the-art at the time of publication. It was not possible to provide detailed information on determining the hottest-spot temperature or magnitude for the many dry-type transformer designs manufactured. The guide also applies to future designs that incorporate different materials or design concepts not currently produced. The working group deemed it impractical to detail winding configurations and possible hottest-spot locations. The manufacturer has the detailed design knowledge and the responsibility for determining the winding hottest-spot rise. When additional information is available, it will be incorporated into future revisions of this guide.

At the time this guide was completed, the Dry-Type Hot-Spot Methodology Working Group had the following membership:

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IEEE Guide for Determination of Hottest-Spot Temperature in Dry-Type Transformers

1. Overview

1.1 Scope

This guide describes methodologies for determination of the steady-state winding hottest-spot temperature in dry-type distribution and power transformers with ventilated, sealed, solid cast, and encapsulated windings built in accordance with IEEE Std C57.12.01-1998 and IEC 60726 (1982-01). Converter transformers are not included in this guide.

1.2 Purpose

Assumptions regarding the relation of winding hottest-spot temperature rise to average winding temperature rise are not representative of all dry-type transformer constructions and winding size. A uniform methodology for determination of winding hottest-spot temperature will provide consistency in testing and calculations for manufacturers' verification of the winding hottest-spot temperature to the user, and for validation and review of winding hottest-spot temperature limits.

1.3 Applications

This guide is applicable to prototype and production unit dry-type transformers.

2. References

This guide is to be used in conjunction with the following publications. When the following publications are superseded by an approved revision, the revision applies.

IEC 60050-426 (1990-10), International Electrotechnical Vocabulary. Chapter 426: Electrical apparatus for explosive atmospheres.[1]

[1]IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

IEC 60726 (1982-01), Dry-type power transformers.

IEEE Std C57.12.01-1998, IEEE Standard General Requirements for Dry-Type Distribution and Power Transformers Including Those with Solid Cast and/or Resin Encapsulated Windings.[2]

IEEE Std C57.12.80-1978 (Reaff 1992), IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.12.91-1995, IEEE Standard Test Code for Dry-Type Distribution and Power Transformers.

3. Definitions

For the purposes of this guide, standard transformer terminology is defined in IEEE Std C57.12.80-1978. Other electrical terms are defined in IEC 60050-426 (1990-10) and the IEEE Standard Dictionary of Electrical and Electronic Terms [B6].[3]

Definitions of terms associated with transformer thermal performance and other terms used in this guide are listed as follows:

3.1 average winding temperature rise: The arithmetic difference between the average winding temperature and the ambient temperature as determined from the change in the ohmic resistance measured across the terminals of the winding in accordance with the test procedures specified in IEEE Std C57.12.91-1995.

3.2 hot-spot: A non-recommended abbreviated term frequently used as a synonym for the maximum or hottest-spot temperature rise of a winding.

3.3 maximum (hottest-spot) winding temperature: The maximum or hottest temperature of the current carrying components of a transformer winding in contact with insulation or insulating fluid. The hottest-spot temperature is a naturally occurring phenomena due to the generation of losses and the heat transfer phenomena. It is the highest temperature inside the transformer winding and is greater than the measured average winding temperature of the coil conductors. All transformers have a maximum (hottest-spot) winding temperature.

NOTE—In this guide, the hottest-spot rise is not considered to be due to localized manufacturing defects.

3.4 maximum (hottest-spot) winding temperature rise: The arithmetic difference between maximum (hottest-spot) winding temperature and the ambient temperature.

3.5 prototype transformer: A transformer manufactured primarily to obtain engineering data or evaluate manufacturing or design feasibility. Prototypes may be pre-production units or units typical of current designs manufactured for test purposes to obtain data to comply with changes in industry standards or for other reasons.

3.6 temperature rise: The difference between the temperature of the part under consideration [commonly the *average winding rise* or the *maximum (hottest-spot) winding temperature rise*] and the ambient temperature.

[2]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://www.standards.ieee.org/).

[3]The numbers in brackets correspond to those of the bibliography in Annex B.

4. Temperature measurement

4.1 Temperature sensors

Applicable temperature measurement devices include

a) Optical temperature sensing device
b) Thermocouples
c) Resistance bridge
d) Infrared temperature detector
e) Temperature labels

4.2 Accuracy

Accuracy in winding hottest-spot temperature measurement is dependent upon placing temperature sensors in the appropriate locations.

Care must be taken to isolate temperature sensors from high voltages and stray magnetic fields. Devices such as thermocouples can give erroneous measurements due to heating and circulating currents caused by electromagnetic fields.

4.3 Attachment of temperature sensors

Thermocouples, fiber-optic temperature probes should be installed within the coil winding or firmly attached to the surface on which the temperature is to be determined. Methodology of attachment (type of adhesive material, amount of adhesive material, surface finish) plays a significant role in the overall accuracy of the surface hottest-spot temperature measurement. Item a) of 5.4.2 details placement of temperature sensors in the winding.

4.4 Temperature measurement methodology

A temperature measurement methodology should be developed and proven by sound experimental principles. Annex A provides background information on how to carry out a verification of a candidate hottest-spot temperature measurement methodology.

4.5 Application

4.5.1 Direct temperature measurement

Direct reading measurement devices are capable of measuring temperature only at the position the devices are located. A sufficient number of devices should be installed to ensure accurate temperature measurement results at the position located.

4.5.2 Surface temperature measurement

Surface temperature can be measured by placing the sensors in intimate contact with the coil surface. Such devices are attached with an appropriate adhesive to maintain firm contact.

The differential temperature between winding hottest spot and coil surface may be determined by measurement or by calculation with a thermal model and added to the surface temperature for determining winding hottest-spot temperature.

4.5.3 Surface hottest-spot measurement and average winding temperature rise

If sufficient surface temperature measurements are made on a winding, coupled with an accurate temperature differential (proven by experiment on models or prototypes) relating surface (encapsulation) temperature to internal winding temperature, it is possible to determine the average winding temperature rise by taking the average of all surface temperature rises (with external to internal correction factor). This is another means of verifying the surface temperature measurement methodology.

5. Determination of winding hottest-spot temperature

5.1 Validation of winding hottest-spot temperature

To demonstrate compliance with winding hottest-spot temperature rise limits, the manufacturer should utilize a proven thermal model for determination of the temperatures throughout each winding and all leads under rated conditions.

Determination of winding hottest-spot temperature rise, using a model that meets the requirements listed herein, should be based upon the detailed design knowledge available to the manufacturer. It is imperative that the manufacturer have data readily available to demonstrate that calculated values are supported by experimental testing. Additionally, the manufacturer should perform analyses to demonstrate that the data supports application of experimental results and mathematical models to the particular design being purchased.

5.2 Effects of winding hottest-spot temperature rise

In determining the winding hottest-spot temperature, the manufacturer should examine each region of the windings and leads where one of the following factors is influencing the local temperatures.

The winding hottest-spot temperature rise is mainly affected by

a) Amount and type of turn and layer insulation
b) Vertical height of winding
c) Radial build or thickness of winding
d) Number of ventilating ducts in winding, size, thickness, and spacing
e) Encapsulation thickness
f) Coil configuration (round/rectangular)
g) Core effects, losses/magnetic effects

5.3 Transformer model

The model should be based on fundamental loss calculations and heat transfer relationships. General allowances for each element of the model are not adequate.

Experimental data should be available to verify model results. Experimental results may include direct reading temperature sensor measurements on production transformers and laboratory models.

5.3.1 Model components

The following elements should be considered in the model:

a) Losses in components subject to added losses, including
   1) End turns in windings
   2) Connections subject to leakage flux, such as some tap to winding connections
   3) Leads

b) The total losses in the subject conductors should be determined using the eddy and circulating current losses in addition to the resistance loss. This requires leakage field analysis to determine the magnitude of the flux and the resulting losses.

c) Added blanketing of current carrying conductors, including
   1) Added tape where conductors exit windings
   2) Regions blanketed by pressboard insulation
   3) Added tape and barriers on leads outside the windings, such as where they pass close to ground
   4) Extra tape in end turns where losses may be higher
   5) Large thickness of epoxy such as the tap area

5.3.1.1 Validity of data

Reliable data for the winding hottest-spot temperature rise can be measured during testing with a sufficient number of direct reading sensors. Proper choice of installation locations is crucial to accurately determine the winding hottest-spot temperature. The manufacturer should have performed calculations that indicate probable winding hottest spots so that sensors can be properly located.

5.4 Prototype thermal tests to develop or validate mathematical models

5.4.1 General

This procedure describes a test methodology using prototype transformers or windings to qualify a design family and the manufacturer's mathematical model. For outer windings remote from the core, test coils should be satisfactory. For inner windings near the core, tests should be performed on a prototype transformer. The loading back test method is the preferred test method to determine winding hottest-spot temperature rise in prototype transformers. The loading back test method requires a greater amount of testing facilities and becomes increasingly difficult to perform as the size of the transformer increases. The procedure described in 5.4.2 permits estimation of the winding hottest-spot temperature rise using the short circuit test method. It gives conservative results when compared with the loading back test method, but should permit manufacturers without facilities for loading back tests to substantiate winding hottest-spot temperature rises in their prototype designs.

5.4.2 Procedure—Short circuit method

a) Install a sufficient number[4] of thermocouples in the windings of a prototype transformer to insure that the winding hottest-spot temperature is measured. Thermocouples should be of small size to minimize conduction errors and the build of the winding. Thermocouple diameters of 0.13 to 0.25 mm are recommended. The coil geometry should be considered in selection of the location with duplicate thermocouples at the anticipated winding hottest-spot location. Placement of thermocouples should be circumferentially around the coil and should include the portion of the lead in contact with insulation within the coil. To develop a mathematical model it is recommended that thermocouples be installed from the bottom to the top of the winding to give a vertical temperature profile.

b) Short the low voltage winding and apply rated current until temperature rises are constant. Record temperatures.

c) Remove the short and apply excitation voltage until temperature rises are constant. Record temperatures.

d) Calculate winding hottest-spot temperature rise for rated conditions by iteration of Equation (1) and Equation (2) until the value of the winding hottest-spot temperature rise converges. It is necessary to perform the calculations for many points in the coil since the core loss affects the temperature distribution non-uniformly. The winding hottest-spot location for the current-only test may be different than for the excitation voltage test and thus different than for a loading back test.

$$\Theta_{C'} = \Theta_C \left[\frac{\Theta_{HS} + T_A + T_k}{\Theta_C + T_{AT} + T_k} \right]^N \tag{1}$$

$$\Theta_{HS} = \Theta_{C'} \left[1 + \left(\frac{\Theta_E}{\Theta_{C'}} \right)^{\frac{1}{N}} \right]^N \tag{2}$$

where

Θ_C is winding hottest-spot temperature rise over ambient during current-only test,

Θ_{CN} is corrected winding hottest-spot temperature rise over ambient due to current only,

Θ_E is winding hottest-spot temperature rise over ambient during excitation voltage-only test,

Θ_{HS} is winding hottest-spot temperature rise over ambient for rated conditions,

T_A is rated ambient temperature, usually 30 ºC,

T_{AT} is ambient temperature during current test,

T_k is 234.5 ºC for copper, 225 ºC for aluminum,

N is 0.8 for self cooled (AA), 0.9 for forced air (FA).

5.4.3 Procedure—loading back method

a) Install temperature sensors in a prototype unit.
NOTE—See 5.4.2, item a).

b) Impress rated excitation voltage at rated frequency per procedure referenced in 11.8.1 or 11.8.2 of IEEE Std C57.12.91-1995 and circulate rated current until temperature rise is stable.

c) Shutdown and record temperatures.

[4]Approximately 25–300 sensors for qualifying a prototype transformer, depending on transformer size.

5.4.4 Application to production transformer designs

Θ_E is determined by tests on a prototype transformer. The value may be scaled for other size transformers by the ratio of core heat flux exiting the core leg by the following equation:

$$\Theta_{E2} = \left[\frac{\Phi_2 A_2 (\rho_{CORE})_2 L_2 D_1}{\Phi_1 A_1 (\rho_{CORE})_1 L_1 D_2}\right]^N \Theta_{E1} \tag{3}$$

where

A is core leg area [square centimeters based on metrification and consistency with 5.4.2, item a)],
D is diameter of core leg (centimeters based on metrification),
L is heated length of winding (centimeters based on metrification),
(ρ_{CORE}) is density of core (kilograms per cubic meter based on metrification),
Φ is heat generated by core leg (watts per kilogram based on metrification),
1 subscript indicates tested unit,
2 subscript indicates different design,
N is 0.8 for self-cooled (AA); 0.9 for forced air (FA).

Annex A

(informative)

Temperature measurement methodology

A.1 Introduction

An approach to determine an accurate hottest-spot ratio for dry-type transformers (hottest-spot rise/average rise) requires the accurate measurement of the average temperature rise and the adoption of a methodology that allows the measurement of hottest-spot temperature in a repeatable and accurate fashion.

The average temperature rise can easily be measured using the well proven *Rd.c. shutdown* method.

The selection of a hottest-spot temperature measurement methodology may involve the testing of many types of temperature reading devices. This will be covered later in this annex.

In order to accurately measure the hottest-spot temperature, knowledge of the location of the *hottest spot* is required.

A.2 Hot-spot location

A.2.1 Embedded temperature sensors

Embedded temperature sensors wound into the winding is the preferred method of determining the hottest-spot location. See 5.4.2, item a).

A.2.2 Surface temperature sensors

For some transformer designs where cooling ducts are accessible and extend completely around the winding, the hottest-spot location may be determined by surface temperature measurements.

A.2.3 Temperature measurement methodology

The first step in determining hottest-spot location is to utilize a temperature measurement methodology where sufficient measurement points can be obtained along the surface of a winding. One simple method is to insert non-reversing temperature indicating labels into a number of cooling ducts for each winding, evenly spaced from top to bottom. Thermocouples, fiber-optic probes, or other suitable temperature indicating devices can be used in a similar fashion. This methodology can be repeated for transformers of various geometries and electrical rating. Typical transformer ratings could yield several hundred measurement points. A proof of the validity of this approach can be demonstrated by taking the average of all label readings (after adding a known temperature differential value for the internal winding temperature and the measured surface temperature) for each particular test to ascertain if an average temperature rise value close to the value derived from the *Rd.c. shutdown* method is yielded.

Plotting the label readings vertically from bottom to top for each monitored cooling duct of a winding should yield consistent definition and location of the hottest spot.

By inserting an appropriate temperature measurement device down a cooling duct, an appropriate distance from the top of each winding and within a winding sector, the hottest-spot temperature can be measured consistently, easily, and accurately for each winding.

A.3 Brief assessment of selected temperature measuring devices

A.3.1 Temperature labels

a) Temperature labels are typically available at eight level temperature step strings. Five label ranges will have to be used to cover 40 to 300 ºC.
b) They are permanent indicating, low cost, and robust.
c) Resolution at best is 4 ºC.
d) Attachment to the surface is critical for accuracy and a rough winding surface could make this difficult. Poor surface contact could create, for instance, a dead air space and possibly produce a low reading.
e) Stickers are calibrated by the manufacturer on horizontal surfaces. Application to the measurement of temperatures on a transformer winding is on a vertical surface.
f) Inconsistent or discontinuous registration of temperature may occur.
g) The measurement system cannot be automated for data collection.

A.3.2 Thermocouples

a) They can be connected to an automated test system. They are reliable, robust, and moderately low cost.
b) Magnetic fields can affect the reading.
c) There are safety issues related to the voltage applied to the transformer winding under test and this must be taken into consideration when using this method.
d) Good contact with the winding surface is a must for good accuracy.

A.3.3 Infrared periscopes

a) Their function is based on a non-contact method.
b) They can be automated and have a fast response time.
c) They are expensive.
d) They suffer from high-voltage isolation problems, as do thermocouples.
e) Device bodies can heat up in magnetic fields, thus affecting results.
f) They are bulky, temperature range limited and require emmissivity calibration (even for so-called broad temperature range types) for maximum accuracy.

A.3.4 Resistor temperature indicating devices (RTDs)

a) The same comments as for thermocouples apply.
b) RTDs tend to have large surface areas that affect readings, small surface RTDs are required.

A.3.5 Fiber-optic temperature transducers

a) The principle of operation of fiber-optic transducers is based on a small crystal embedded in the tip of a fiber-optic strand that emits a different wave length of light at different temperatures.
b) Proper attachment to the winding surface is critical.
c) Current technology can be expensive, but costs are improving.

d) Probes and leads are fragile and use in an industrial lab environment is a consideration.
e) Measurement system can be automated.
f) High-voltage isolation is inherent.

A.4 Temperature measurement device comparison methodology

This clause will summarize some of the consideration in the comparison of various hottest-spot temperature measurement devices for the purpose of selecting the most appropriate devices and method of attachment to the winding surfaces.

A.4.1 Back-to-back comparison

The temperature devices should be checked using a *back-to-back* comparison methodology. One option is to use a hotplate with a 25 mm thick aluminum plate to increase thermal mass and to provide *buffering* from the heater elements. This test can be repeated with insulation and encapsulation layers to model a winding more realistically.

The temperature measurement devices should be checked simultaneously to fully assess performance. See Figure A.1 for an illustration of test set up.

A.4.2 Verification with boiling water

Another method of comparatively assessing temperature measurement devices and method of attachment is to use a glass beaker filled with boiling water. Temperature measurement devices can be placed in the water (method of attachment not evaluated) or attached to the surface of the beaker (method of attachment to be evaluated). The use of boiling water to verify that a temperature measurement device is registering accurately is a standard procedure. An added feature is the evaluation of the method of attachment to a surface.

Method of attachment to the surface should be trialed and assessed e.g., silicone rubber, epoxy glue, etc. The amount of material used to attach the temperature measurement device to the surface is a critical factor and can impact the result. Experience has shown that silicone rubber caulking compound is one of the easiest materials to work with. Adhesion is excellent on all surfaces, temperature performance capability is high, and it is easy to control the amount of material.

A.4.3 Flat-slab windings

Another method of evaluating temperature measurement devices is to fabricate *flat-slab windings* using the same conductor, insulation system and encapsulation materials as those employed in the transformer windings on which hottest-spot temperature measurement are to be made. The winding is done in a zig-zag (back and forth) fashion in a flat plane, which results in a *slab* resistor. The slab-resistor winding can be energized at various current densities (surface watt loss) with the slab in a vertical orientation. Various temperature measurement devices can be attached at the same horizontal location, allowing a *back-to-back* comparison of performance accuracy to be made.

A.4.4 Evaluation of conductor to surface temperature differential

For both the hot plate and the flat slab methods, the *simulated conductor* can be measured and used as a basis for evaluating the conductor temperature to surface temperature differential. Care should be taken to have controlled and steady power input, i.e., use a microprocessor controlled temperature controller rather than a mechanical thermostat.

These precautions are not necessary with the water beaker because of its inherent calibration and stability. However, this is true of only two temperatures: 0° and 100 °C. Other temperatures would require the same precautions for the hot plate and flat slab methods.

A.4.5 Sample test results

Some typical temperature results are provided in Table A.1.

Table A.1—Sample test results

Setup	Thermocouples	Temperature labels	Infrared
Hotplate	83.6 °C	82 °C	93 °C
Winding simulation	77.1 °C	82 °C	89 °C

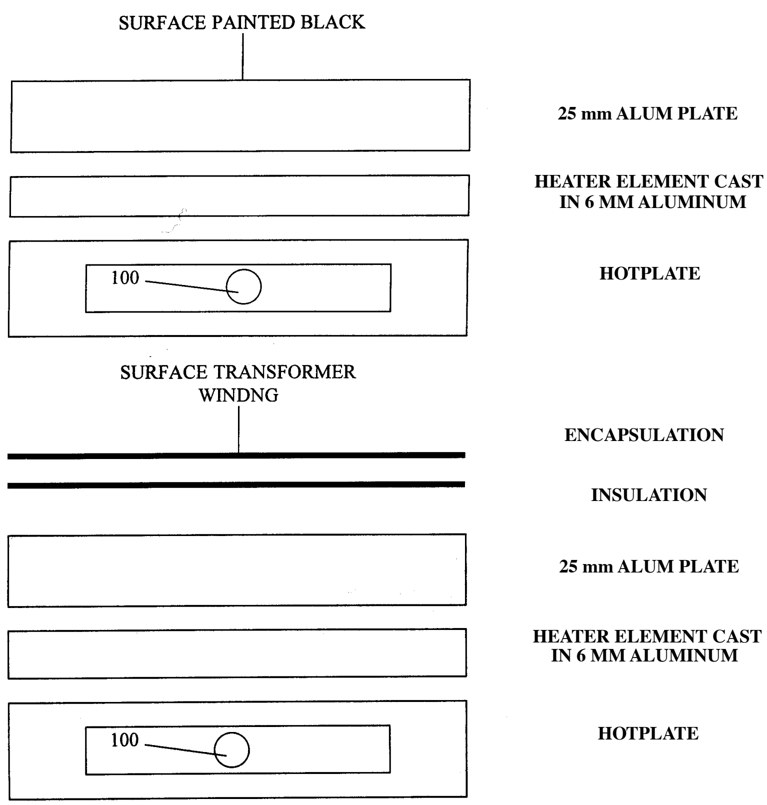

Figure A.1—Equipment setup

Annex B

(informative)

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